Propagation of edge magnetoplasmons in semiconductor quantum-well structures

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The wavelength and the propagation length of the edge magnetoplasmons, running along the edge of a two-dimensional electron layer in a semiconductor quantum-well structure are theoretically studied as a function of frequency, magnetic field, electron density, mobility, and geometry of the structure. The results are intended to be used for analysis and optimization of operation of recently invented quantum-well microwave spectrometers operating at liquid-nitrogen temperatures (I. V. Kukushkin *et al*, Appl. Phys. Lett. **86**, 044101 (2005)).

Recently, a new method of detection and spectroscopy of microwave radiation has been discovered [1, 2, 3]. The method is based on excitation and interference of a special type of plasma waves – edge magnetoplasmons (EMP) [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25] – in a semiconductor quantum-well structure. The EMPs propagate in a two-dimensional (2D) electron system along its edge and possess two important physical properties. First, their frequency is tunable across a very broad frequency range (experimental observation of EMPs have been reported at frequencies from ~ 1 kHz [15] up to ~ 1 THz [11]). Second, in contrast to the bulk plasmons and magneto-plasmons, their damping is small not only at $\omega\tau \gg 1$ but at any value of $\omega\tau$, if the applied magnetic field is sufficiently strong ($\omega_c\tau \gg 1$). Here ω and ω_c are the microwave and the cyclotron frequencies, and τ is the momentum relaxation time. These two EMP properties open unique opportunities to build resonant (frequency sensitive) detectors and spectrometers for the microwave and terahertz frequency range [1, 2, 3, 26].

In the experiments [1, 2, 3], a quantum-well semiconductor sample with a 2D electron gas (EG) is placed in an external magnetic field and irradiated by microwaves. Radiation excites EMPs in the near-contact regions of the sample. EMPs, emitted from different contacts, propagate along the edge of the 2DEG and interfere with each other. This leads to the microwave induced photovoltage between pairs of contacts, proportional to $|1+\exp(iqL)|^2$, where L is the distance between the contacts and $q(\omega)$ is the EMP wavevector directed along the edge of the 2DEG. This photovoltage oscillates as a function of the applied magnetic field, with the oscillation amplitude and period proportional to the microwave power and wavelength respectively, which allows one to use the effect for frequency-sensitive detection and spectroscopy of radiation.

Due to scattering of electrons in the sample, the wavevector $q(\omega)$ is a complex function, with the real part $q'(\omega)$ determining the EMP wavelength and the imaginary part $q''(\omega)$ – their decay length. For proper device operation, q' must be larger than q'' and the parameter $e^{-q''L}$ should not be too small. The quantities $q'(\omega)$ and $q''(\omega)$, apart from the radiation frequency, also depend on the magnetic field B, the 2D electron density n_s, the mobility of 2D electrons $\mu = e\tau/m^\star$ (and hence on the temperature) and dielectric environment of the sample. The goal of this letter is to quantitatively analyze these dependencies, so that this information could be used for analysis and optimization of device operation.

First, consider a 2DEG lying on the boundary of a semiconductor substrate (the dielectric constant κ) with air. In this case, the EMP dispersion equation [10] can be written as $Y = G(X)$, where $Y = (\omega + i/\tau)/\omega_c$,
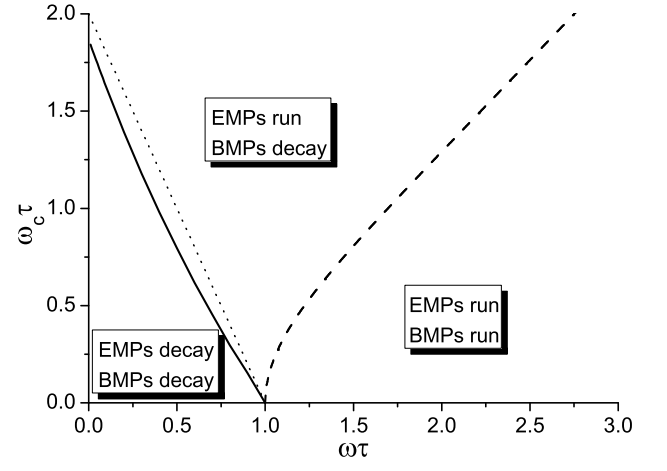
$$G(X) = \tanh\left\{\frac{1}{\pi}\int_0^{\pi/2} dt \ln\left(1 + \frac{X}{\sin t}\right)\right\}, \quad (1)$$

$$X = \frac{2\pi n_s e^2 q(\omega + i/\tau)}{m^\star \bar{\kappa}\omega(\omega_c^2 - (\omega + i/\tau)^2)}, \quad (2)$$

and $\bar{\kappa} = (\kappa + 1)/2$ [the bulk magnetoplasmon (BMP) dispersion relation [27] has the form $1 + X = 0$]. If $F = G^{-1}$ is the inverse function of G, $X = F(Y)$, the above equations can be written as

$$Q \equiv \frac{2\pi n_s e^2 q}{m^\star \bar{\kappa}\omega^2} = \frac{\omega_c^2 - (\omega + i/\tau)^2}{\omega(\omega + i/\tau)} F\left(\frac{\omega + i/\tau}{\omega_c}\right). \quad (3)$$

One sees that both real and imaginary parts of the wavevector q are inversely proportional to the electron density, and that the dimensionless complex wavevector Q is a function of two parameters, $\omega_c\tau$ and $\omega\tau$. Figure 1 shows Q as a function of dimensionless magnetic field ω_c/ω at several different values of $\omega\tau$. The imaginary part Q'' can be well approximated, for all curves in Figure 1, by the formula

$$Q'' \approx \frac{1.217}{\omega\tau}\left(1 + 0.09\frac{\omega_c\tau}{\sqrt{1+\omega^2\tau^2}}\right). \quad (4)$$

As seen from Figure 1, if $\omega\tau > 1$, Q' is always bigger than Q'', EMPs can propagate in the sample, and their
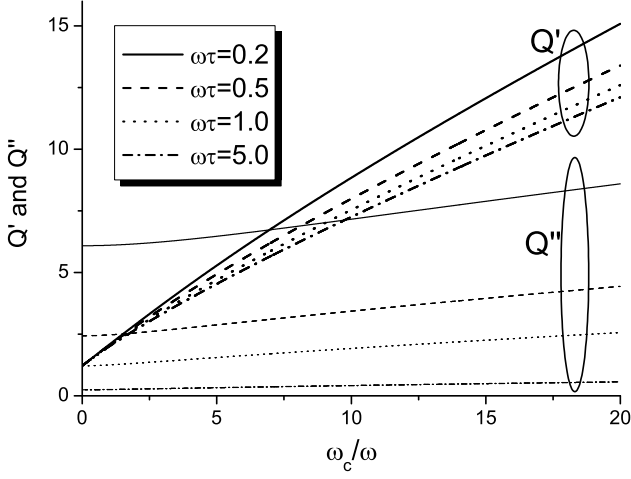
FIG. 4: The same as in Figure 3b but for $\omega/\omega_0 = 4$. The pairs of solid and dashed curves correspond to (from top to bottom): $\omega_0\tau = 0.5$, 1, 2, and 10.
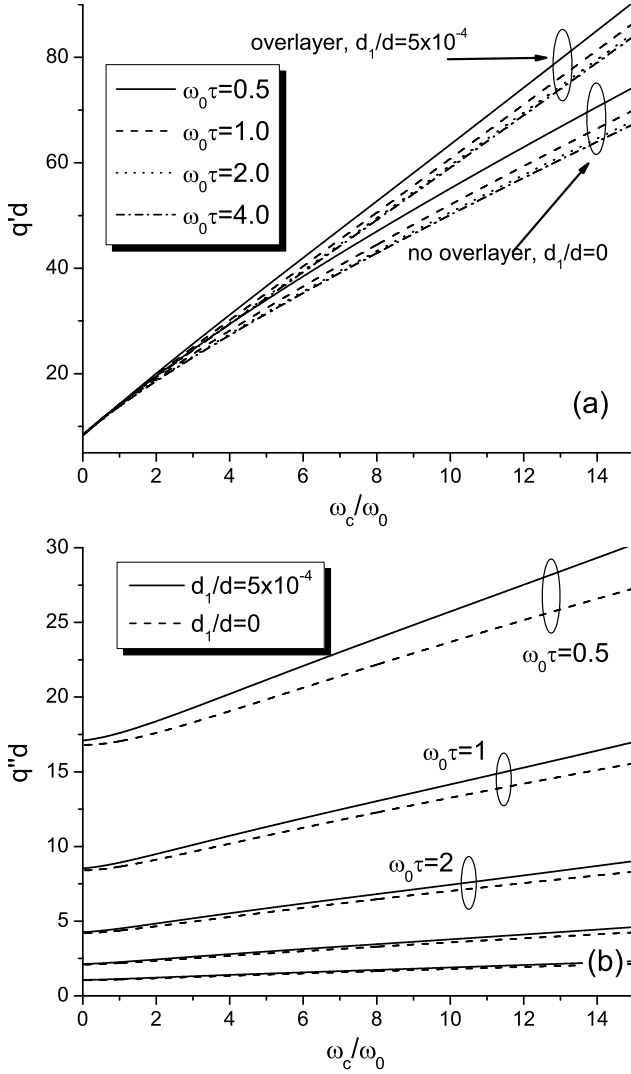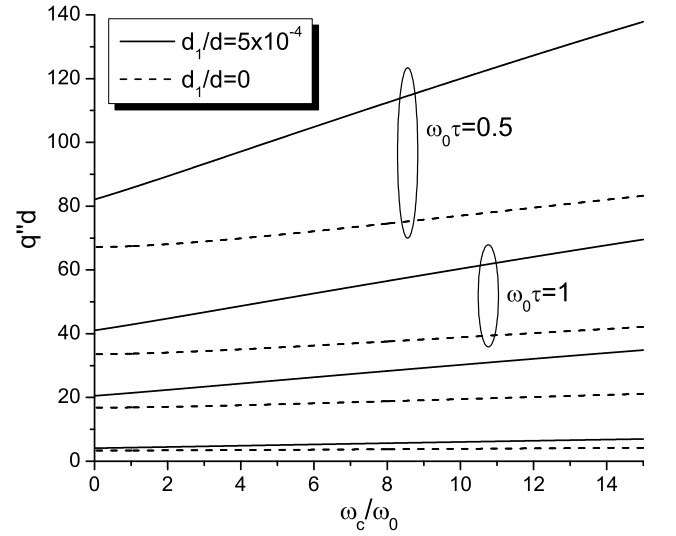
and information about running experiments.

FIG. 3: (a) Real and (b) imaginary parts of the dimensionless wavevector qd as a function of dimensionless magnetic field ω_c/ω_0 at different values of $\omega_0\tau$ in structures with ($d_1/d = 5 \times 10^{-4}$) and without ($d_1/d = 0$) the overlayer. Two lowest pairs of curves in Figure (b) correspond to $\omega_0\tau = 4$ and $\omega_0\tau = 8$. The microwave frequency is $\omega/\omega_0 = 1$, which corresponds to about 50 GHz at experimental parameters [1, 2, 3].

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